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August 19, 1957

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Dear Sir:

Enclosed please find three (3) copies of Progress Report No. 6 on our Project No. A-100 covering the month of June, 1957.

Expenditures during the month of May amounted to \$2214.56, and in June \$2008.72, leaving an uncommitted and unexpended balance of approximately \$14,350.98.

Sincerely yours,

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RWB/es

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Project No. A-100
THICKNESS MEASUREMENT OF
NON-METALLIC MATERIALS

Progress Report No. 6

for

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August 19, 1957

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THICKNESS MEASUREMENT OF NON-METALLIC MATERIALS

I. INTRODUCTION

This is a report of the progress on Project No. A-100 for the period of June 1 through June 31, 1957. The purpose of this project is to develop an ultrasonic instrument for measuring the thickness of non-metallic materials with the measurements being confined to one face of the sample. Since the measurements would be quite difficult in concrete, because of the rough surface and inhomogeneous structure and the consequent poor coupling and high attenuation, it was chosen for the sample material. Thus, if the method finally devised will work in concrete, it should work in many non-crystalline materials. Most of the measurements have been made on concrete blocks with foot-square faces and a thickness of three or six inches.

The two methods of measuring thickness ultrasonically are the determination of the resonant frequencies of the sample and the measurement of the travel time of a pulse in the sample. When access to both sides is possible the measurement is relatively simple by either method, and the procedure is standard enough that equipment for making these measurements, even in concrete, is commercially available. A transmitter is placed on one face and a receiver on the other, and either the frequencies where peaks occur in the transmitted energy or the travel time for a single pulse are measured. (In the first case, the measurement may be refined by observing the relative phase of the two transducers.) The thickness can then be found easily. In the resonance method, the thickness is known to be a half wavelength ($\lambda/2$) or an integral number (n) of half wavelengths at resonance. Since the wavelength is the velocity of sound in the material divided by the frequency (c/f) we have

$$s = (n) \lambda/2 = (n) c/2f \quad (1)$$

In the pulse method the thickness is given by

$$s = ct \quad (2)$$

where t is the travel time of the pulse.

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If the velocity of sound in the material under consideration is known, the thickness is then known to the same degree of accuracy. When a second, independent, measurement can be made this accuracy can be improved.

If the resonant frequencies can be measured with access to only one face, equation (1) still holds. Here the resonance might be measured either by the increased power drawn by the transducer or by placing a detector near the transmitter. In the pulse-echo method, if the time required for a pulse to traverse the sample and return can be measured and is taken as $2t$, equation (2) again gives the thickness of the sample. Separate transmitters and receivers may be used, as when the measurement is made from one face to the opposite face, or a combined transmitter-receiver may be used. Instruments, in the case of which only one side need be accessible, are commercially available for measuring the thickness of metals by either the resonance or pulse-echo technique.

The commercially available equipment will not work on concrete, mainly due to the fact that the high frequencies with which the units operate are attenuated rapidly in concrete. The attenuation is due largely to the inhomogeneities in the concrete which often have dimensions of the order of a wavelength at these frequencies. (One megacycle per second gives a wavelength in concrete of 0.2 inches.) To reduce this scattering attenuation, frequencies of the order of 100 kilocycles per second must be used. Many measurements in concrete, particularly in measurements through large structures, are made with frequencies of the order of 20 kilocycles per second. This, of course, limits the resolution, for a 20 kcps compressional disturbance in concrete has a wavelength of approximately eight inches.

Further problems arise when the lateral dimensions of the sample are comparable to the thickness. In addition to the longitudinal or compressional waves, transverse or shear waves and surface waves are produced in the sample. These latter waves cause spurious indications, particularly when the resonance method is used. This result was also found in the work being conducted at [redacted] The investigators there found that this interference did not disappear until the transverse dimensions were of the order of several yards compared to a thickness of a foot or so.

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G. Bradfield, at the National Physical Laboratory in England, has succeeded in measuring the thickness of concrete or mortar blocks, using the pulse-echo method with two transducers placed on one face of the sample. He reports that some trouble is experienced with interference due to the waves propagated along the surface, the interference being minimized by adjustments in the position and orientation of his asymmetrical transducers.

Most of the work at [] has been based on the use of the pulse-echo technique. To date, resonance experiments have shown little promise. No clear indications of resonance have been obtained when the measurements were confined to one side of the sample. These results can be understood when it is realized that some portion of the signal introduced must pass through the sample, be reflected at the far side, and return to the sender in order for resonance to be established. Thus, we are faced with the same problem as in the pulse-echo technique but a problem compounded by size considerations. Because of the attenuation in the concrete, the beam cannot diverge appreciably or the return signal will be too weak to establish resonance. To insure that the beam does not diverge the smallest dimension of the transducer face must have a length which is comparable to the wavelength of the disturbance in the sample. Yet, the velocity of sound in barium titanate is of the same order of magnitude as the velocity of sound in concrete and so the transducer will have resonances in the same frequency range as the concrete. The solution is to damp the transducer or to make it with lateral dimensions that are several wavelengths. Obtaining enough damping has thus far proved impossible and the use of a very large transducer does not seem to provide the most feasible approach. These problems do not exist in metals since there is much less attenuation there and since higher frequencies can be used, with resonances occurring at the higher harmonics (n greater than one in equation (1)).

Comparing the behavior of concrete to that of metals, the reasons for our present problems with the use of the pulse-echo technique are apparent. The main problem is the attenuation in concrete and the resultant low value of the reflected signal, in addition to the low frequencies that must be used. The problem here is not so much in the amplification of this signal, for this can be done, but rather in the inability to separate the start of the signal from the background due to the slow decay of the initial pulse.

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As mentioned above, the transmitter and receiver functions can either be separated in two transducers or combined in one. If the functions are to be combined in one transducer, the remnant ringing of the transducer due to the originating pulse must be lower than the signal due to the reflected pulse. The difficulties in detection due to the signal attenuation in concrete are compounded by the low frequencies used and the short time that must be measured. For example, if we wish to measure a three inch thickness of concrete with a pulse of 100 kilocycle per second waves, the travel time of the pulse is only 30 microseconds or three periods of the oscillation. This means that the transducer ringing must be considerably down at the conclusion of three periods.

The use of a second transducer as a receiver does not eliminate this difficulty, for the shear and surface waves will transmit the ringing from the transmitter to the receiver. Bradfield eliminated this by placing the two rather far apart, but for small concrete blocks this would not be possible. The desired effect might also be accomplished by heavily damping both transducers and placing them close enough that the signal due to the interfering waves has died out before the return of the reflected longitudinal wave. This latter might be accomplished by using, as the transmitter, a ring concentric with a center disc serving as a receiver.

Once the above difficulties have been surmounted the amplification of the received signal and the measurement of the travel time can be accomplished with any of a number of standard devices.

II. WORK TO DATE

It is evident that the problems are essentially those of damping the transducers and coupling the transducers to the concrete. Early work had indicated several possibilities of damping. Five barium titanate ceramic discs (one inch in diameter and one-fourth inch thick), which had rather similar characteristics, were chosen for tests on damping. In preliminary tests, various backing materials were attached to these discs by vaseline and later by household glue. The best of the configurations were then repeated with the bonding being made with Epon 828, a polymerizing cement. (A polymerizing type of bonding agent is needed since a cement that depends on evaporation of a volatile component may have air pockets or weak spaces in the center of the bonded area.) The first configurations used were:

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1. Two ceramics bonded together with a sheet of metal between them to provide electrical contact.
2. A steel disc, one-fourth inch thick, bonded to the back of a ceramic.
3. A bakelite disc, one inch thick, bonded to the back of a ceramic.

The results from the above led to the construction of a fourth configuration where the ceramic disc was set in the center of a three inch square bakelite plate of the same thickness as the ceramic.

Some of the results on these configurations are shown in Table I. Here are listed the values of the transducer impedance, in arbitrary units, for the resonant and anti-resonant frequencies associated with the radial mode (in the region of 120 kcps) and the thickness mode (in the region of 400 kcps).

TABLE I
TRANSDUCER IMPEDANCES AT RESONANCE

	Typical ceramic alone	Bakelite-backed	In bakelite plate
Resonant frequency (in cps)	116	118	112
Impedance (in arbitrary units)	3.5	35	58
Anti-resonant frequency	119	125	116
Impedance	1480	140	70
Resonant frequency	396	380	393
Impedance	4	25	26
Anti-resonant frequency	401	388	404
Impedance	740	72	80

Table I does not show the minor resonances, of which there are quite a few and rather more in the more highly damped ceramics. However, the weak resonances that appear in all units are damped to the same degree

as the main resonances by the added backing. Thus, Table I does furnish a reasonable indication of the overall behavior.

It was also found that the steel-backed ceramic had a strong new resonance which was at a frequency roughly one-half that of the former thickness resonance. This was associated with a reduction of the peak near 400 kcps. Such behavior was expected on theoretical grounds and may also prove useful in controlling the frequency response of the final transducer.

The ratio of the impedances at the anti-resonant and resonant frequencies is related to the Q or "ringiness" of the transducer. This is brought out in Table II, which gives the results of an actual measurement of the ringing of the transducer in the bakelite plate and that of the steel-backed transducer. (The ringing of the latter already being somewhat lower than that of a free transducer.) In both cases the units were pulsed with a 25 volt pulse with a duration of approximately eight microseconds, which duration seemed to give the least ringing.

TABLE II
COMPARISON OF RINGING

	Oscillation during pulse	After 30 μ sec.	After 50 μ sec.	After 100 μ sec.
Ceramic in bakelite plate	250 mv	100 mv	25 mv	10 mv
Steel-backed ceramic	200 mv	1000 mv	750 mv	300 mv

The value of the signal induced in the concrete was also measured by a transducer on the face opposite to that on which the above senders rested. The signal from the ceramic mounted in the plate was found to be insignificantly larger.

The feasibility of damping by a viscous liquid was also investigated further. The materials tested were glycerine, castor oil, mineral

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oil, several cellulose gum solutions, vaseline, and a silicon damping compound. The cellulose gums were found to have too high an electrical conductivity to allow operation of the transducer when immersed in the material. The silicon compound gave higher damping than the vaseline but both were inferior to the castor oil and mineral oil. The best of the materials tested was the glycerine. The damping of the glycerine far exceeded that in the bakelite plate. However, this advantage over the bakelite plate is more than offset by the decreased signal to the concrete when the transducer is operated in glycerine in any holder designed so far.

The amount of damping produced when various couplants were placed between an undamped transducer and a concrete block was used to assess the relative merits of the couplants. Here it was found that any of the liquids tried (the same group as used in the above tests on damping by immersion, with the important addition of ordinary tap water) gave essentially the same results. Vaseline and the silicon grease seemed to give very poor coupling, that is, the transducers were not very highly damped when these materials were placed between the transducer and the concrete. The chief differences among the liquids lay in the damping of the radial mode, which, of course, is now to be accomplished by the imbedment of the transducer in a bakelite plate. The mineral oil seemed to give the greatest damping of the radial mode with glycerine and castor oil as close seconds. Water gave rather poor damping on the radial mode. This might be taken to indicate that water would give the most satisfactory coupling since the poorer coupling of the radial mode may be desirable in order to reduce the shear and surface waves.

The electronic pulser originally built in the Acoustics Section has also been re-designed to give much shorter pulses. Although the pulse still consists of a rapid rise followed by an exponential decay, the voltage applied to the transducer is effectively back to zero after a period of approximately ten microseconds. This allows the examination of the behavior of the transducer, or the transducer-concrete system, at much shorter intervals after the initiation of the pulse.

III. FUTURE WORK

The investigation should continue along much the same lines. Some points that will be considered in more detail are the problem of the

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electronic pulse or signal generator, the possibility of electronically damping the transmitting transducer, and the possible utilization of the damping supplied by glycerine.

IV. NOTEBOOKS

The work reported here is recorded in [] Notebooks C-6529 and C-6880.

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V. CONTRIBUTING PERSONNEL

The work continues under the direction of [] Most of the experimental work has been done by [] with some consultation with []

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Respectfully submitted,

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APPROVED:

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